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NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

REPORT No. 401

COMBUSTION IN A HIGH-SPEED COMPRESSION-IGNITION ENGINE

By A. M. ROTHROCK



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AERONAUTICAL SYMBOLS

1. FUNDAMENTAL AND DERIVED UNITS

	Symbol	Metric		English	
		Unit	Symbol	Unit	Symbol
Length-----	l	meter-----	m	foot (or mile)-----	ft. (or mi.)
Time-----	t	second-----	s	second (or hour)-----	sec. (or hr.)
Force-----	F	weight of one kilogram-----	kg	weight of one pound-----	lb.
Power-----	P	kg/m/s-----		horsepower-----	hp
Speed-----		km/h-----	k. p. h.	mi./hr.-----	m. p. h.
		m/s-----	m. p. s.	ft./sec.-----	f. p. s.

2. GENERAL SYMBOLS, ETC.

W , Weight = mg	mk^2 , Moment of inertia (indicate axis of the radius of gyration k , by proper subscript).
g , Standard acceleration of gravity = 9.80665 m/s ² = 32.1740 ft./sec. ²	
m , Mass = $\frac{W}{g}$	S , Area.
ρ , Density (mass per unit volume).	S_w , Wing area, etc.
Standard density of dry air, 0.12497 (kg-m ⁻⁴ s ²) at 15° C. and 760 mm = 0.002378 (lb.-ft. ⁻⁴ sec. ²).	G , Gap.
Specific weight of "standard" air, 1.2255 kg/m ³ = 0.07651 lb./ft. ³ .	b , Span.
	c , Chord.
	$\frac{b^2}{S}$, Aspect ratio.
	μ , Coefficient of viscosity.

3. AERODYNAMICAL SYMBOLS

V , True air speed.	Q , Resultant moment.
q , Dynamic (or impact) pressure = $\frac{1}{2}\rho V^2$.	Ω , Resultant angular velocity.
L , Lift, absolute coefficient $C_L = \frac{L}{qS}$	$\frac{Vl}{\mu}$, Reynolds Number, where l is a linear dimension.
D , Drag, absolute coefficient $C_D = \frac{D}{qS}$	e. g., for a model airfoil 3 in. chord, 100 mi./hr. normal pressure, at 15° C., the corresponding number is 234,000;
D_o , Profile drag, absolute coefficient $C_{D_o} = \frac{D_o}{qS}$	or for a model of 10 cm chord 40 m/s, the corresponding number is 274,000.
D_i , Induced drag, absolute coefficient $C_{D_i} = \frac{D_i}{qS}$	C_p , Center of pressure coefficient (ratio of distance of $c. p.$ from leading edge to chord length).
D_p , Parasite drag, absolute coefficient $C_{D_p} = \frac{D_p}{qS}$	α , Angle of attack.
C , Cross-wind force, absolute coefficient $C_c = \frac{C}{qS}$	ϵ , Angle of downwash.
R , Resultant force.	α_o , Angle of attack, infinite aspect ratio.
i_w , Angle of setting of wings (relative to thrust line).	α_i , Angle of attack, induced.
i_t , Angle of stabilizer setting (relative to thrust line).	α_a , Angle of attack, absolute.
	(Measured from zero lift position.)
	γ , Flight path angle.

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HIGH-SPEED COMPRESSION-IGNITION ENGINE**

**By A. M. ROTHROCK
Langley Memorial Aeronautical Laboratory**

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

NAVY BUILDING, WASHINGTON, D. C.

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SUMMARY

An investigation, conducted by the National Advisory Committee for Aeronautics, to determine the factors which control the combustion in a high-speed compression-ignition engine is presented. Indicator cards were taken with the Farnboro indicator and analyzed according to the tangent method devised by Schweitzer. The analysis shows that in a quiescent combustion chamber increasing the time lag of autoignition increases the combustion efficiency of the engine and also increases the maximum rate of combustion. Increasing the maximum rate of combustion increases the tendency for detonation to occur. The results show that by increasing the air temperature during injection the start of combustion can be forced to take place during injection and so prevent detonation from occurring. It is shown that the rate of fuel injection does not in itself control the rate of combustion.

INTRODUCTION

During the last few years the development of the high-speed compression-ignition engine has resulted in the production of several commercial types. There are at present two compression-ignition engines for aircraft use, the Packard and the Junkers, which have passed 50-hour Government tests. There are, in addition, several engines in the experimental stage. The development of the engines has been fraught with many difficulties. It is encouraging to realize that these difficulties are being overcome. The successful metering and injecting of extremely small quantities of fuel was realized with the introduction of the direct injection fuel pump. In fact, the development of the pump has reached such a stage that there is considerable interest being shown in the practicability of substituting the pump for the carburetor on spark-ignition aircraft engines.

The hardest problem to solve in the development of the high-speed compression-ignition engine for aircraft has been that of mixing and burning the fuel and air. Recent results in this country, in Germany, and in England have shown that methods for forming a good combustible mixture are being worked out. The results have been shown in the low fuel consumptions that have been obtained with aircraft compression-ignition engines. However, all the air in the combustion chamber has not been utilized. The present high-speed compression-ignition engine burns

only 70 to 80 per cent of the available air in the combustion space.

Summarizing the present-day results for aircraft engines: The fuel consumption of the compression-ignition engine is approximately 0.40 pounds per horsepower-hour compared with 0.55 pound per horsepower-hour for the spark-ignition engine; the brake mean effective pressure of the compression-ignited engine is approximately 95 pounds per square inch compared with 130 pounds per square inch for the spark-ignition engine. We can conclude, therefore, that the compression-ignition engine, because of its high cycle efficiency, gives fuel consumptions superior to the spark-ignition engine; but that, because all the air in the combustion chamber of the compression-ignition engine is not utilized, the power delivered by a compression-ignition is less than the power delivered by the spark-ignition engine of the same displacement. The problem resolves itself, therefore, into one of obtaining better mixing and burning of the fuel and air in the combustion chamber of the compression-ignition engine.

During an investigation conducted at the Langley Memorial Aeronautical Laboratory at Langley Field, Va., on the effect of injection valve and injection nozzle design on engine performance, indicator cards were obtained for various engine-operating conditions. From the interpretation of these cards, much can be learned of the combustion process and of the factors which control the combustion process in the high-speed compression-ignition engine suitable for aircraft service. It is the purpose of this report to present such an analysis and, in addition, the conclusions that can be drawn from the analysis relative to the process of combustion.

APPARATUS

The indicator cards were obtained from an N. A. C. A. Universal test engine (reference 1) operated as a compression-ignition engine. The engine had a bore of 5 inches, a stroke of 7 inches, and a compression ratio of 12.6:1. All tests were made at an engine speed of 1,500 r. p. m. The combustion chamber of the engine (fig. 1) was of the vertical-disk form. It was so designed that the air flow in it produced by the motion of the piston was negligible. The mixing of the fuel and the air was obtained by proportioning the orifices in the discharge nozzle so that all the air in the

chamber was served by the fuel jets issuing from the multiorifice discharge nozzle. The tests conducted to obtain the performance of the engine with different nozzle designs have been described by Spanogle and Foster. (References 2 and 3.) An N. A. C. A. Roots blower (reference 4) was used to supply air at pressures greater than atmospheric pressures. These tests have been described by Spanogle and Foster in reference 5. For one series of tests an injection valve containing two stems was employed. The purpose of this valve was to give an initial injection of fuel to certain parts of the combustion chamber before the main injection to the remaining parts of the chamber. The tests with this injection valve have been described by Spanogle and Whitney in reference 6.

The indicator cards were obtained with the Farnboro indicator as altered by the staff of the Langley Memorial Aeronautical Laboratory. (Reference 7.)

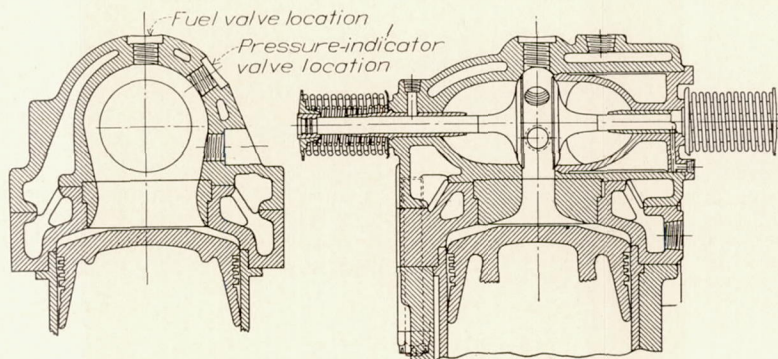


FIGURE 1.—N. A. C. A. vertical disk combustion chamber

The method by which the rate of fuel discharge from the injection valve into the atmosphere was determined has been described in reference 8. The total fuel quantity determined by this method was in every case greater than the amount injected into the combustion chamber of the engine for the same injection pump and injection valve setting. This discrepancy can be partly accounted for by the higher pressures into which the fuel was discharged when the injection valve was mounted in the engine. The rates of fuel discharged shown on the figures are in every case the rates obtained with the injection valve discharging into the atmosphere. For computing the various efficiencies of the engine the total fuel quantity actually discharged into the engine was used.

METHOD OF ANALYZING THE INDICATOR CARDS

The indicator cards were analyzed according to the method devised by Schweitzer. (Reference 9.) As Schweitzer has shown, the rate of heat input to or output from the gases in the engine can be expressed by the relationship

$$\frac{dQ}{dv} = p \frac{c_p}{R} \left(\frac{c_p}{c_v} + \frac{v}{p} \frac{dp}{dv} \right) \quad (1)$$

in which—

$\frac{dQ}{dv}$ = the rate of heat change with respect to volume.

p = the instantaneous pressure at the instantaneous volume v under consideration.

c_p = the specific heat at constant pressure.

c_v = the specific heat at constant volume.

R = the universal gas constant.

Schweitzer has also shown that this equation can be simplified into—

$$\frac{dQ}{dv} = \frac{\frac{c_p}{c_v} + \frac{v}{p} \frac{dp}{dv}}{\frac{c_p}{c_v} - 1} p \quad (2)$$

in which the dimensions of dQ are LM ; that is, if v is in units of cubic inches and p in units of pounds per square inch, dQ is in units of pound inches. Equation (2) eliminates the necessity of computing R .

Equation (2) can be changed into

$$\frac{dQ}{d\theta} = \frac{\frac{c_p}{c_v} + \frac{v}{p} \frac{dp}{d\theta} \frac{d\theta}{dv}}{\frac{c_p}{c_v} - 1} p \frac{dv}{d\theta} \quad (3)$$

in which θ is in crankshaft degrees. Using

Schweitzer's method $\frac{v}{p} \frac{dp}{dv}$ can be determined

directly from the $p-v$ diagram. As the piston approaches top center the tangents drawn to the $p-v$ curve have such a slope that the accuracy with which they can be drawn is not

sufficient for the analysis of the curve. In this range, therefore, equation (3) is used, as $\frac{dp}{d\theta}$ is less than $\frac{dp}{dv}$.

For the use of equation (3) the $p-v$ diagram is transferred to a $p-t$ diagram in which the time is expressed as crank degrees.

In the use of either equation all the quantities are obtained directly from the indicator card and the dimensions of the engine with the exception of c_p and c_v . The values of the specific heats change according to both the constituents in the combustion chamber and the temperature in the chamber. The temperature range met with in the tests, the results of which are presented in this report, was from approximately 1,300° F. absolute to 3,000° F. absolute. The equations for the effect of temperature on the specific heats of the various gases have been given by Goodenough and Felbeck. (Reference 10.)

In the analysis approximations were used from time to time. These approximations considerably shortened the analysis and were in all cases within the experimental error. It is well to emphasize at this time that the purpose of this analysis is not to find absolute values but to learn the main factors which effect the

combustion process in the combustion chamber of the high-speed compression-ignition engine. In determining the values of $\frac{c_p}{c_v}$ the actual temperatures were

not determined, since the rate of variation of $\frac{c_p}{c_v}$ in the range included in the investigation was too slight to warrant computations of $\frac{c_p}{c_v}$ at each point in the cycle.

Instead, the values were determined for the maximum temperature and for the temperatures at the end of compression and the end of expansion points. On the $p-v$ diagram a straight-line relationship was assumed

between the value of $\frac{c_p}{c_v}$ at the maximum temperature and the values of $\frac{c_p}{c_v}$ at the end of compression and the

end of expansion. It was assumed that in all cases there was 100 per cent excess air in the cylinder at all times and the specific heats computed for this condition. For a more complete discussion of the possible errors arising in the analysis the reader is referred to Schweitzer's original paper. (Reference 9.)

After the rate of heat input was determined from equations (2) or (3) the rate of fuel burned was determined by computing the amount of fuel necessary to liberate the energy at the rate of heat input. The lower heating value of 18,300 B. t. u. per pound of fuel was used for this purpose. From the rate-of-fuel-burned curve the total amount of fuel burned, disregarding heat losses, was obtained. The ratio of the total amount of fuel burned to the total amount of fuel injected is the combustion efficiency of the engine. The ratio of the total amount of energy expended on the piston to the total amount of energy liberated from the fuel burned is the cycle efficiency of the engine. The product of the cycle efficiency and the combustion efficiency is the thermal efficiency of the engine. The total amount of energy expended on the piston and the indicated mean effective pressure were obtained from the $p-v$ diagram. The variation of the indicated mean effective pressure obtained from the diagrams from the indicated mean effective pressure obtained by adding the brake mean effective pressure to the friction mean effective pressure was, in general, not more than 5 per cent.

PRECISION OF RESULTS

The precision of the results depends upon the accuracy with which the pressure-time curve can be drawn from the points on the indicator card taken with the Farnboro indicator and the accuracy with which the tangents to the curves can be drawn. Figure 2 shows a contact print of the original card from which the data shown in Figure 17 were obtained. The points show the deviation of the pressures in the engine from cycle to cycle. The compression line shows little variation. The points recorded during the combus-

tion process show an appreciable deviation from the mean values. For this section of the card the curve was drawn to obtain average values. With this particular record two contact prints were made and the curves were drawn on them. To prevent the possibility of the second card being drawn in part from memory the curve on the second card was drawn several days after that on the first. The data from the curves were tabulated and drawn on a $p-v$ diagram. (Fig. 3.) The deviation becomes noticeable on the explosion curve and on the latter part of the expansion curve. The two $p-v$ diagrams were then analyzed with the results shown on the figure.

Figure 4 shows the rates of combustion for the two $p-v$ diagrams shown in Figure 3. The variation becomes noticeable at the maximum rates of burning and again during the period of after burning. The final results from the two diagrams are as follows:

	Indicated mean effective pressure from card (pounds persquare inch)	Fuel burned (pound)	Combustion efficiency (per cent)	Cycle efficiency (per cent)	Thermal efficiency (per cent)
C	152	0.000302	70.3	40.5	28.4
C'	152	.000288	67.0	42.5	28.4
Mean	152	.000295	68.7	41.5	28.4
Maximum deviation, per cent	0	5	5	5	-----

from which it can be concluded that the precision is sufficient for the present analysis.

Figure 5 shows the comparison of rates of combustion determined from equations (2) and (3). The figure shows that the use of either equation gives precise results when the quantities $\frac{dp}{dv}$ or $\frac{dp}{d\theta}$ are not excessive.

ACCURACY OF EXPERIMENTAL RESULTS

The accuracy of the experimental results can be estimated from a comparison with the results of theoretical researches on the cycle of the internal-combustion engine. Consider the results presented in Figure 14. The air charge taken into the cylinder was 0.00618 pound. (Reference 5.) Assume that the fuel burned from 10° before top center to 10° after top center burned at constant volume, and that the remainder of the fuel burned at constant pressure. The fuel burned at constant volume was 0.000105 pound and the fuel burned at constant pressure was 0.000137 pound. Following the general method given by Ellenwood, Evans, and Chwang (reference 11), the cycle efficiency, indicated mean effective pressure, and the indicator card were computed. The computed values are compared with the experimental values in Figure 6. The compression curves show little variation. The maximum cylinder pressures show an appreciable deviation. During the 10° revolution of the crank

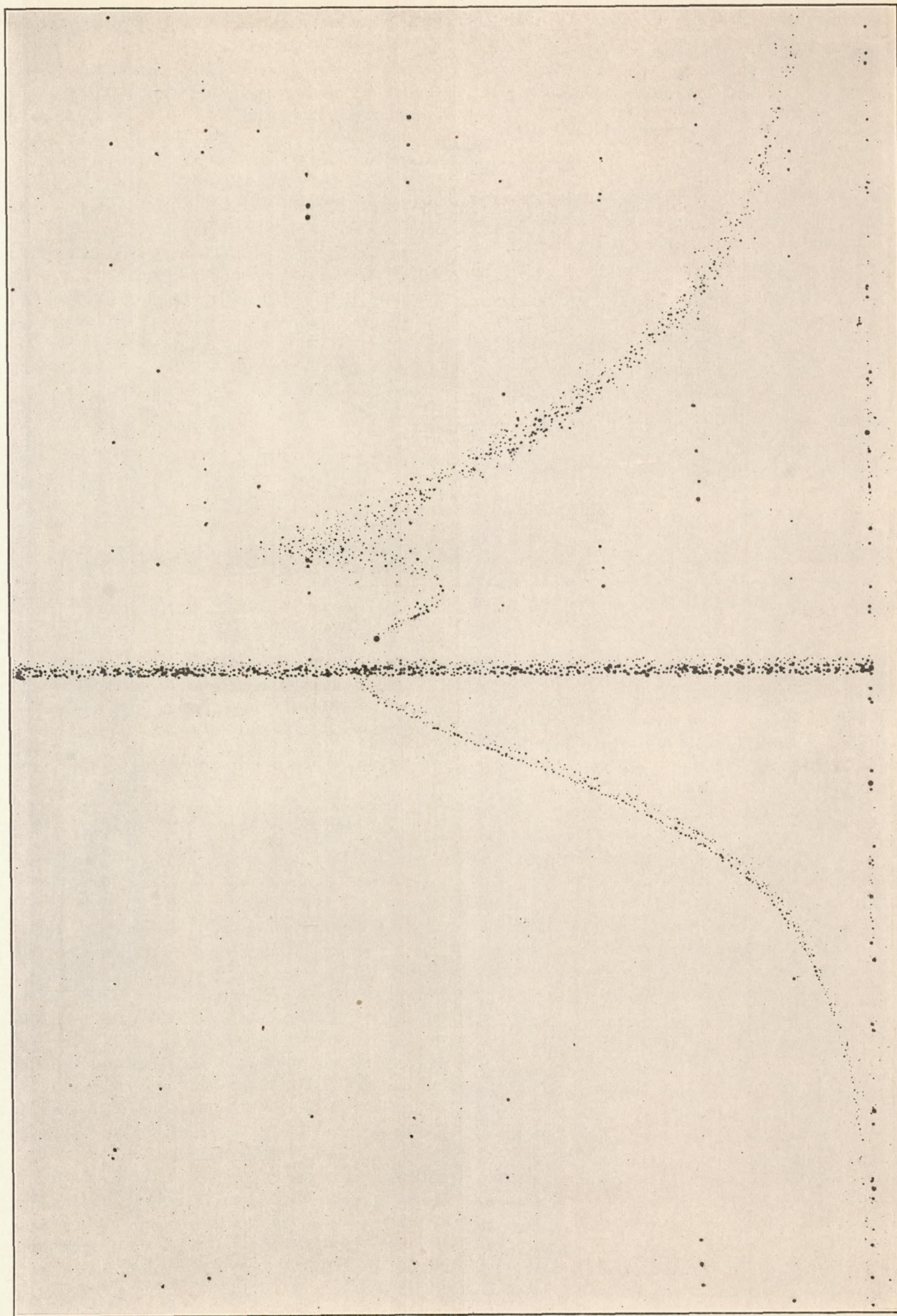


FIGURE 2.—Indicator card taken with Farnboro indicator

after top center the volume in the cylinder increased 10 per cent. If the maximum computed cylinder pressure is corrected for this increase in volume, the value becomes 950 pounds per square inch, which compares favorably with the experimentally determined value of 930 pounds per square inch. The analysis shows that the fuel in the cylinder continued to burn until 60° after top center, corresponding to a stroke of 2 inches. The end of combustion on the theoretical card occurs at a stroke of 0.25 inch. Consequently, the experimentally determined indicator card shows a less rapid rate of pressure drop between top center and the stroke of 2 inches. After this point the slope

to the constant-volume cycle and then according to a cycle employing neither constant volume nor constant pressure. The cycle efficiency of the engine increases as the amount of fuel burned at constant volume is increased. However, increasing the amount of fuel burned at constant volume increases the tendency for detonation. In addition, the high maximum cylinder pressures encountered in the constant-volume cycle increase the stresses on the engine. Just how much the weight of the engine must be increased because of these high cylinder pressures is not known. The late Capt. L. M. Woolson has shown how, by ingenious design, these increased stresses may be withstood

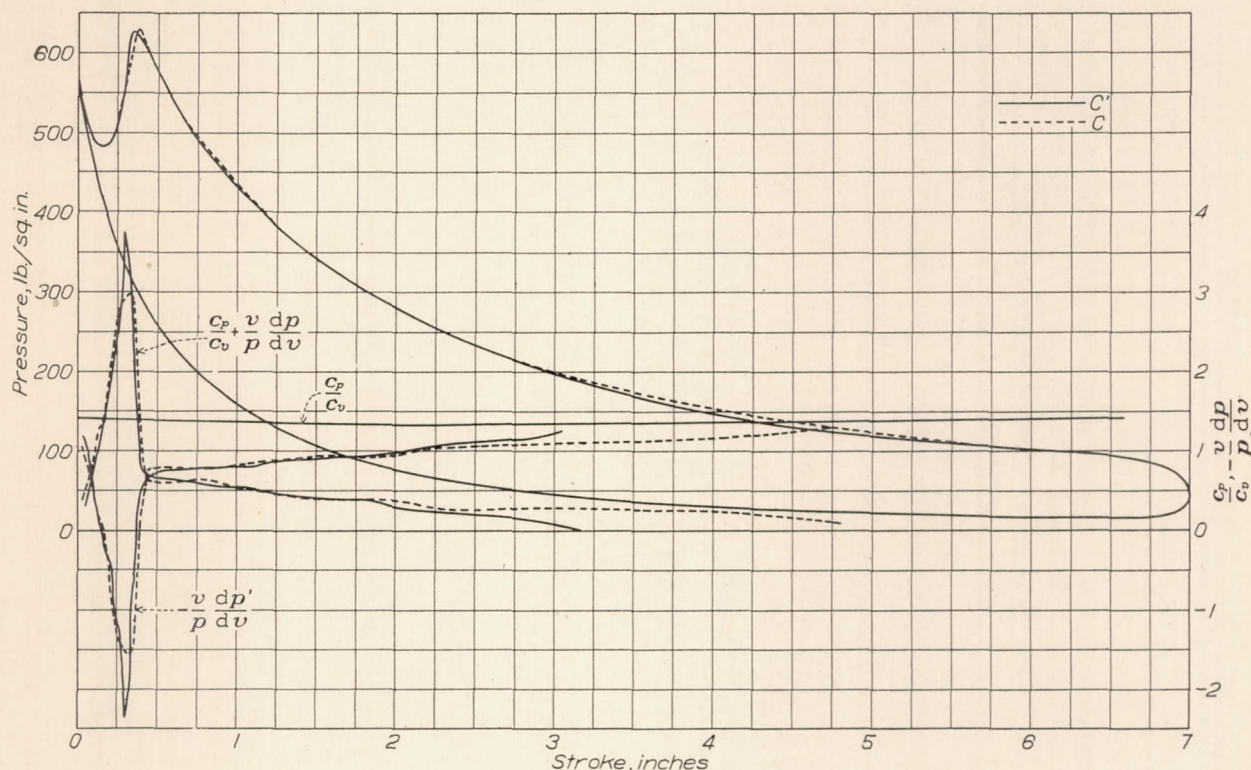


FIGURE 3.—Precision of tangent method of analysis

of the curves becomes quite similar. The higher pressure on the experimental card at the end of the stroke indicates that there was more energy lost to the exhaust gases than the cycle efficiency indicates. The higher indicated mean effective pressure on the actual card also indicates that the total fuel quantity burned was greater than the computations show. However, the difference in the indicated mean effective pressures (6 per cent) is not sufficient to affect the present analysis. The errors in the computations are partly caused by the values chosen for the specific heats and by the fact that the analysis does not consider the change in constituents of the gases during combustion.

Figure 6 shows that the combustion process in modern high-speed compression-ignition engines does not follow the constant-pressure cycle upon which Diesel based the design of his original engine. In general, the combustion first proceeds approximately according

without increasing the weight of the engine to any great extent.

ANALYSIS

The ignition of the fuel drops in air has been investigated in this country, in England, and in Germany. Tests with constant-pressure bombs have been conducted to measure both the ignition temperature and the ignition lag. The early results gave ignition lags in excess of those obtained in the engine. The most recent results of Bird (reference 12) have, however, given lags as low as 0.004 second. The experimentally determined ignition temperatures have shown considerable variation, depending on the apparatus used. Bridgeman and Marvin (reference 13) have given a comparison of the results obtained by several investigators. Bridgeman and Marvin concluded that "There is a different self-ignition tempera-

ture for every experimental apparatus and procedure." They also state that the true self-ignition temperature of the fuel is a fundamental property of the fuel and dependent only upon the total pressure and concentration. They define this true ignition temperature as "the minimum temperature which must be reached by instantaneous heating of an element of volume within a homogeneous combustible mixture to initiate inflammation or explosion instantaneously."

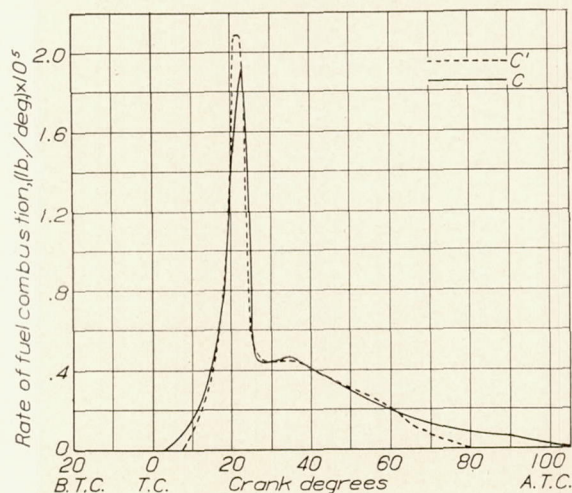


FIGURE 4.—Precision of rate of combustion

This true self-ignition temperature can not be determined directly by experiment, and it is doubtful whether for compression-ignition engine research it is necessary to determine it.

In addition to the ignition temperature as defined by Bridgeman and Marvin, there is the minimum temperature at which auto ignition of the fuel will take place. This temperature has been investigated by Tausz and Schulte (reference 14) and by Neumann. (Reference 15.) In discussing this temperature Tausz and Schulte state that "The temperature

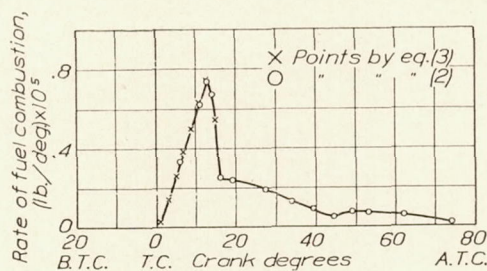


FIGURE 5.—Comparison of results obtained by using equations (2) and (3)

of ignition is independent of whether the fuel is present in the form of a vapor or of a fog and whether in this latter case the drops are large or small. On the other hand, — — — the fineness of subdivision does influence the course and particularly the velocity of combustion and the velocity of propagation of the explosion flame." Tausz and Schulte concluded from their experimental results that increasing the pressure of the air decreased the minimum autoignition tempera-

ture. Neumann extended the autoignition investigations and found that it was not the pressure but the density of the air that affected the minimum autoignition temperature. Quoting from Neumann, "The higher, therefore, the initial temperature of the compressed air lies above the ignition temperature of the fuel, the shorter the ignition delay. This depends, as can be demonstrated, on the rapid increase in the reaction speed with rise in temperature. Without this influence, the rapid decrease in the ignition delay can not be explained alone by the physical effect of the heat transmission resulting from the difference in temperature between the air and the fuel. In a Diesel engine, therefore, the ignition delay is inversely proportional to the temperature variable [difference between air temperature and minimum autoignition temperature] of the fuel, the temperature of the air and the turbulence of the flow in the combustion chamber at the beginning of the ignition." The results of these investigators have also shown

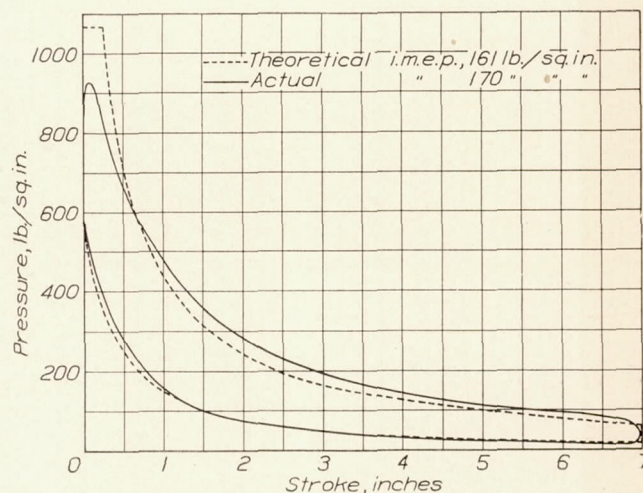


FIGURE 6.—Comparison of actual and theoretical indicator cards. Fuel-air ratio=0.0392 lb. fuel per lb. air. Supercharging pressure=8.75 in. Hg. Cycle efficiency: Theoretical=53.6 per cent, actual=56.6 per cent

that the fuels used in compression-ignition engines ignite at a lower temperature than the fuels used in a spark-ignition engine. These conclusions are extremely important in analyzing results obtained with compression-ignition engines.

Once the fuel-air mixture is ignited, the next problem becomes one of propagating the burning to all parts of the mixture. The speed of propagation will depend, among other things, upon the mixture ratio at the various points in the combustion chamber. The only data which have been published on the distribution of the fuel within the spray cone have been those obtained by Schweitzer and DeJuhasz. (Reference 16.) These results showed that under the densities encountered in the engine cylinder the distribution at 4 inches from the discharge nozzle with a plain round discharge orifice is not uniform. Their data also indicate that the uniformity of the

distribution decreases as the nozzle is approached. The researches of the National Advisory Committee for Aeronautics have shown that to obtain penetrations as high as 4 inches during the time available for injection in high-speed compression-ignition engines it is necessary to use plain round-hole orifices. Although there are no direct data available, it can probably be concluded from spray photographs that the distribution is improved by employing helically grooved stems in the injection valve, by causing two or more fuel jets to impinge on each other close to the discharge nozzle, by employing rectangular orifices, or by causing the spray to strike a metal surface soon after it issues from the discharge orifice. All the above methods are, however, accompanied by a decrease in the spray penetration so that unless the combustion chamber is small the fuel will not reach all the air.

In the present investigation the nozzle contained several round-hole orifices so distributed as to serve all the air in the combustion chamber. However, although fuel did reach most of the air in the chamber

distributed to permit good mixing of the fuel with the air until some time after the end of injection.

Distribution can be materially affected by air flow in the combustion chamber, although test results have indicated that the air velocities must be high to have much effect on the fuel spray in the combustion chamber. (Reference 21.) In this case, instead of the fuel penetrating to all the air, the air is brought to the fuel. There is one outstanding case of the successful use of air flow with a fuel spray from a single round-hole orifice. Ricardo, using such a combination, has obtained a brake mean effective pressure of 112 pounds per square inch. The Junkers and the Packard aircraft compression-ignition engines both obtain good results by the use of air flow in conjunction with special discharge nozzles. Ricardo (reference 22) has published indicator cards obtained on his engines. These cards show that ignition can be initiated soon after the start of injection by employing air flow in the combustion chamber, but that combustion will proceed for a certain time independent of the rate of fuel injection. At the end of this interval the combustion

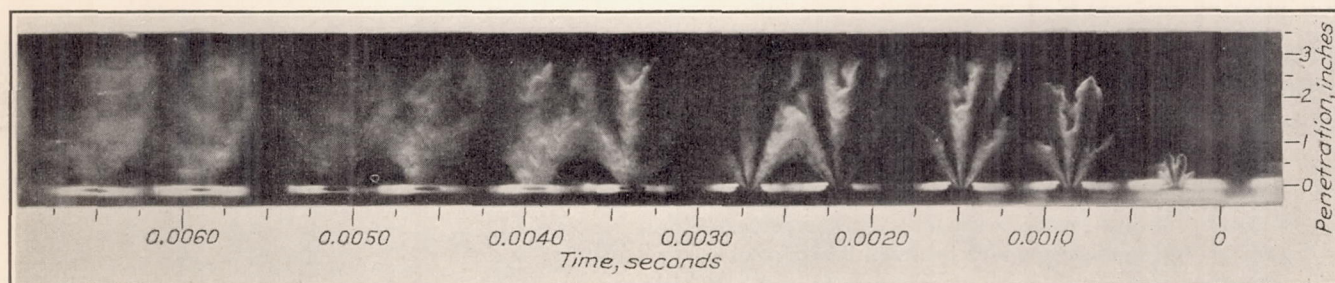


FIGURE 7.—Dispersion after end of injection of sprays from multiorifice nozzle. Injection pressure 6,000 pounds per square inch. Chamber pressure 200 pounds per square inch. Still air

the fuel-air ratio was not uniform throughout the chamber. Instead there were areas varying from lean mixtures to rich mixtures. The results of Kuehn (reference 17), Woltjen (reference 18), Sass (reference 19), and Lee (reference 20) have shown that the spray was probably sufficiently well atomized so that combustion could proceed rapidly once the air-fuel mixture was correct.

The spray photographs obtained with the N. A. C. A. fuel spray photography equipment have shown that during injection the fuel spray shows little tendency to mix with the air surrounding it, but that after the end of injection the fuel tends to diffuse throughout the chamber. (Fig. 7.) It is possible that once combustion has started the burning will aid in mixing the remainder of the fuel with the air. It is doubtful, however, that such mixing will materially aid in the combustion of the fuel. We find, therefore, that in combustion chambers employing no air flow, sprays from plain round orifices must be employed to obtain the necessary penetration; but that, although these sprays are sufficiently well atomized to promote efficient combustion, they are not sufficiently well

distributed to permit good mixing of the fuel with the air until some time after the end of injection. It can not be expected, however, that combustion will necessarily proceed according to this process under operating conditions different from those employed by Ricardo.

Although air flow will aid in the combustion of the fuel, care must be exercised in employing it. Neumann (reference 15) has shown that when the excess of the air temperature over the minimum autoignition temperature of the air was low, air flow increased the ignition lag. (Fig. 8.) As the excess temperature was increased the ignition lag was decreased to a value less than that with still air. Bird (reference 12) was able, by using sufficiently high air flow, to suppress ignition. Hesselman (reference 23) found that too great an air flow increased the fuel consumption of his engine. There was, however, a definite value of flow which gave him his lowest fuel consumption.

Bird (reference 12) also found that the ignition lag and rate of burning were proportional to the excess air coefficient. The ignition lag decreased as the excess air coefficient was decreased, but the time of burning increased as the excess air coefficient decreased.

Whether or not combustion will start during the injection depends upon the temperature and pressure conditions in the combustion chamber. The time lag between the beginning of injection and the start of combustion decreases as the temperature of the air becomes greater than the ignition temperature of the fuel, because of the higher rate of heat input into the fuel drops. (Reference 15.) If the time lag of ignition for the conditions in the combustion chamber is greater than the period of injection, combustion will

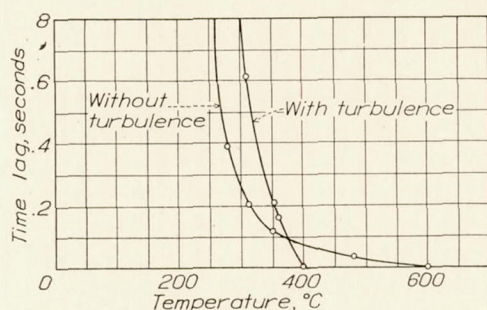


FIGURE 8.—Effect of turbulence on the time lag of autoignition

occur after all the fuel is in the chamber, and most of the burning will approach the constant-volume cycle. If, however, the time lag is less than the injection period, the fuel in the combustion chamber at the start of combustion will burn at very nearly constant volume, whereas the remainder of the fuel will burn at a rate depending upon how it is injected and the time required for it to become mixed with the remaining air and be brought to the autoignition temperature. If the combustion starts before injection is completed, the time lag of ignition of the fuel which is injected

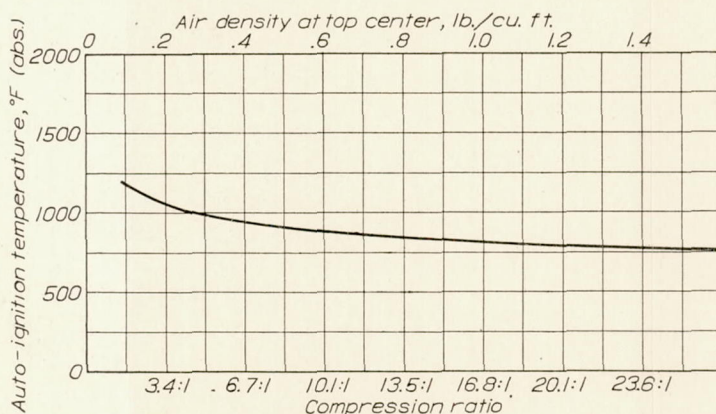


FIGURE 9.—Effect of air density at top center and compression ratio on minimum autoignition temperature

after combustion starts will be less than that injected before combustion starts, because the excess of the temperature in the combustion chamber over the minimum autoignition temperature will increase.

The question arises whether or not it is advisable to have ignition start before all the fuel is in the combustion chamber. If ignition does not start until all the fuel is in the combustion chamber, the maximum rate of combustion and consequently the maximum rate of

pressure rise are only dependent on the speed of the chemical reaction throughout the chamber. If this speed is too great, the pressure rise may be of sufficient rapidity to cause detonation which may reach destructive magnitudes such as was experienced in some of the early work at the Langley Memorial Aeronautical Laboratory. (Reference 24.) Also, if all the combustion takes place close to top center, most of the fuel will burn at constant volume, resulting in extremely high maximum pressures and necessitating a rugged engine to withstand them. Combustion taking place between 10° before and 10° after top center closely approximates constant-volume combustion, since the total change in volume for a compression-ignition engine varies about 10 per cent over this range. If, however, the combustion can be decelerated so as not to be completed until, say, 20° after top center, the volume will have increased approximately 40 per cent. This increase in volume will cause a decrease in the maximum pressures and, because of the slower rate of

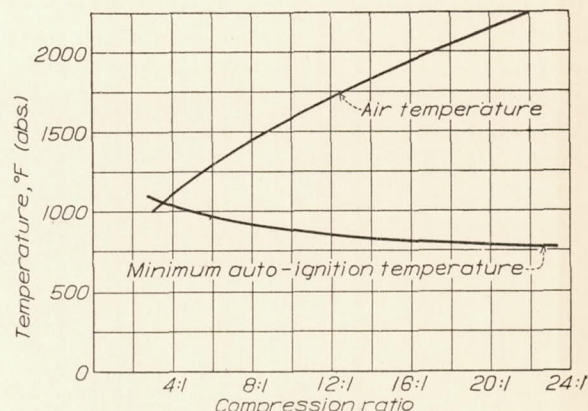


FIGURE 10.—Effect of compression ratio on air temperature at top center and on minimum autoignition temperature

combustion, cause a decrease in the tendency for detonation to occur.

We may therefore conclude that in a compression-ignition engine unless the rate of combustion can be controlled by the variation of the drop sizes and mixture ratio of the atomized fuel, or by its chemical properties, the combustion should be forced to start before the end of injection. The autoignition lag can be decreased by starting the injection close to top center or by increasing the temperature or density of the air.

An idea of the effect on combustion of varying the compression ratio, the inlet-air density, and the inlet-air temperature can be obtained from a brief analysis of the effects of the different variables on the difference between the compression temperature of the air and the minimum autoignition temperature.

Figure 9 shows Neuman's results for the effect of air density on the minimum autoignition temperature. The curve shows that for the range of densities for compression-ignition engine operation there is little change in the minimum autoignition temperature.

Figure 10 shows the effect of compression ratio on the minimum autoignition temperature and on the air temperature at top center. The values for the air temperature were obtained from reference 11. The

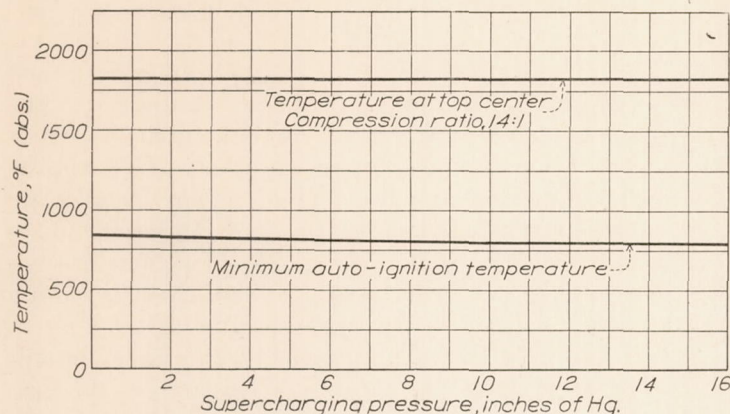


FIGURE 11.—Effect of supercharging on difference between air temperature at top center and minimum autoignition temperature

curves show that increasing the compression ratio from 10:1 to 17:1 (approximately the present limits in compression-ignition engines) increases the temperature difference from 700° F. to 1,150° F. The curve explains why high compression ratios have been resorted to in the development of the high-speed compression-ignition engine for aircraft service. The curve also shows that increasing the compression ratio decreases the tendency for detonation to occur in the engine, because the fuel is forced to ignite earlier, and consequently the initial combustion takes place before all the fuel is in the combustion chamber.

Figure 12 shows the effect of supercharging on the difference between the compression temperature and the minimum autoignition temperature caused by the increase

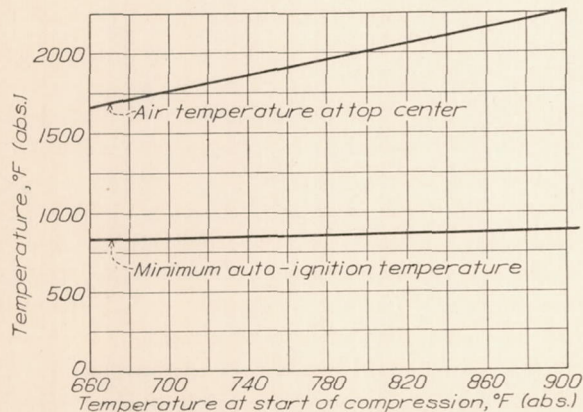


FIGURE 12.—Effect of temperature at start of compression on air temperature at top

center and on minimum autoignition temperature at top center $\frac{V_2}{V_1} = \left(\frac{T_1}{T_2} \right)^{\frac{1}{n-1}}$
 $n=1.35$

in air density. There is little variation over the range of 0 to 14 inches of mercury supercharging. Conse-

quently it can not be expected that increasing the density of the incoming air in an engine will in itself have much effect on decreasing the ignition lag and the tendency for detonation.

Figure 13 shows the effect of increasing the temperature of the air at the start of compression on the difference between the compression temperature and the minimum autoignition temperature. The minimum value of 660° F. absolute is chosen from the temperature assumed by Ellenwood, Evans, and Chwang. (Reference 11.) The curves show that an increase in the intake-air temperature of 100° F. increases the temperature difference from 830° F. to 1,050° F. The decrease by weight of the air charge for this temperature difference is approximately 15 per cent, which will reduce the power output of the engine. Whether or not this decrease in air consumption is justified depends on the improvement in the cycle and combustion efficiencies obtained by the earlier start of ignition.

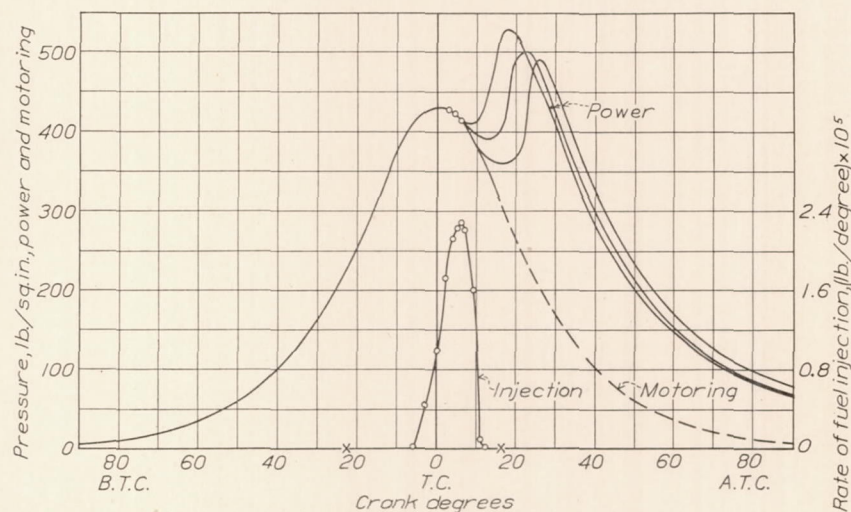


FIGURE 13.—The effect of injection advance angle on combustion

TEST RESULTS AND DISCUSSION

Effect of injection time on combustion.—Figure 13 shows the effect of the timing of the injection on the combustion characteristics of the engine. The fuel-pump setting remained the same for each test. Consequently, the rate-of-injection curve is not reproduced for each test. The start and stop of injection are dependent to some extent on the conditions in the engine because the pressure of the air in the combustion chamber acting on the end of the injection-valve stem tends to lower the injection-valve opening pressure, so the start and stop of injection indicated on the rate-of-discharge curve by X were not necessarily the start and stop of injection with the valve mounted in the engine. There is, however, one point on the rate-of-injection curve that can be used as a reference point. The effect of opening the by-pass valve in the fuel pump on the rate of injection occurred 6nL/s degrees after the opening of the by-pass valve in the injection pump, in which

n is the engine r. p. m., L is the length of the fuel passage between the pump and the injection valve, and s is the velocity with which the pressure waves in the injection system are transmitted through the injection tube. (Reference 25.) For the conditions under consideration this value was 6° . In all cases the small circles on the pressure-time curves represent

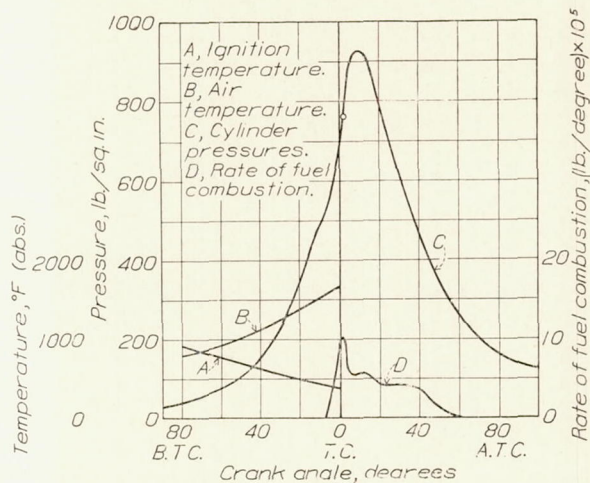


FIGURE 14.—Injection cut-off 2° A. T. C. Fuel-air ratio 0.0392 lb. fuel per lb. air. Supercharging pressure=8.75 in. Hg. i. m. e. p.=170 lb./sq.in. Cycle efficiency=56.6 per cent. Combustion efficiency=58.8 per cent. Thermal efficiency=33.3 per cent

a time of 6° after the cut-off at the pump. The remaining discharge after this point was caused by the residual pressure in the injection line and by the time required for the by-pass valve to open fully and for the injection-valve stem to reach its seat. A more complete discussion of this phenomenon will be found

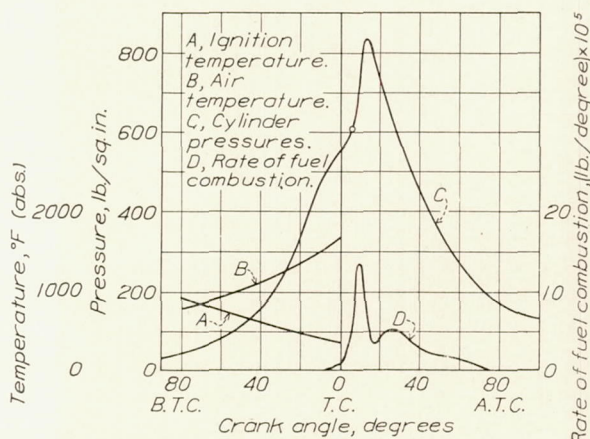


FIGURE 15.—Injection cut-off 6° A. T. C. Fuel-air ratio=0.0427 lb. fuel per lb. air. Supercharging pressure=8.75 in. Hg. i. m. e. p.=166 lb./sq. in. Cycle efficiency=50.5 per cent. Combustion efficiency=63 per cent. Thermal efficiency=31.8 per cent

in reference 25. In the figure the compression line is reproduced as a dashed line on the expansion stroke. The point at which the expansion curve leaves this line is the point at which the energy supplied by the combustion of the fuel became sufficiently great to cause a change in the pressure in the combustion chamber. From this point the curves indicate that the com-

bustion was accelerated until a maximum rate of burning was reached slightly before the maximum pressure; the rate of combustion then dropped, first rapidly, and then, because of afterburning, more slowly. The curves show that as the cut-off of injection was advanced toward top center the time lag between the point of cut-off and the start of combustion decreased considerably. In no case were the conditions in the engine such as to force rapid combustion and so cause the consequent pressure rise to start before all the fuel was injected into the engine. Consequently the rate of combustion was independent of the rate of injection, but dependent only on the conditions of temperature, density, and mixture within the combustion chamber. In this series of tests, as the start of ignition was advanced, the detonation of the engine became more intense until it reached a magnitude that was objectionable.

Figures 14 to 18 show the effect of the time of injection on the combustion characteristics and rates of combustion when a supercharging pressure of 8.75

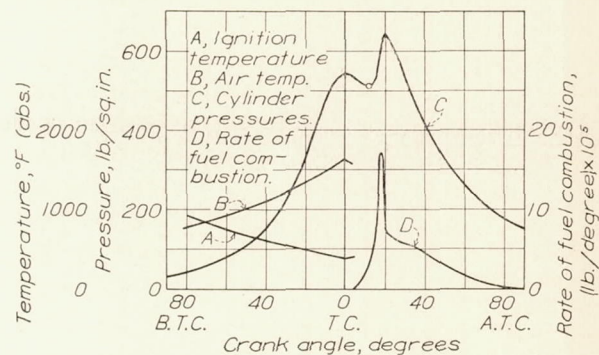


FIGURE 16.—Injection cut-off 12° A. T. C. Fuel-air ratio=0.0445 lb. fuel per lb. air. Supercharging pressure=8.75 in. Hg. i. m. e. p.=152 lb./sq. in. Cycle efficiency=46 per cent. Combustion efficiency=64 per cent. Thermal efficiency=29.5 per cent

inches of mercury was used. The fuel-air ratios refer to the fuel quantity completely burned as obtained from the analysis. For this degree of supercharging the intake temperature was raised from 95° to 125° F. so that there was an additional effect of increased temperature. The curves show, in general, the same effects that are shown in Figure 8. However, with the supercharging and the increased temperature the ignition was forced to occur before all the fuel was injected when the injection cut-off occurred close to top center. (Fig. 14.) The curves show that as the combustion took place nearer top center the cycle efficiency of the engine was increased because of the greater effective expansion ratio. As the cut-off of injection was advanced toward top center the maximum rate of combustion decreased. The conditions shown in Figure 14 approach the desired conditions for high performance. The combustion efficiency was, however, too low to obtain the desired fuel consumption.

The combustion efficiency excludes the amount of heat lost to the cooling water, which was not deter-

mined. In the tests conducted by Schey and Rollin (reference 26) on a similar spark-ignition engine it was found that the losses to the cooling water decreased as the compression ratio of the engine was increased. For a compression ratio of 7:1 the loss to the cooling water was 15 per cent of the total energy input to the engine. This value does not, of course, include the additional losses to the surrounding air from the cylinder head. It does include a certain amount of heat absorbed from the exhaust gases as they passed through the exhaust valve. If we consider a figure of 15 per cent as reasonable for the radiation losses we see that the combustion efficiencies are raised from approximately 58 to 73 per cent and from 67 to 82 per cent. The loss caused by incomplete combustion is still excessive. As has been mentioned before, the spray must be compact to penetrate through the air in the combustion chamber, but this compactness prevents the correct mixture of air and fuel from being obtained. Ellenwood, Evans, and Chwang have shown (reference 11) that decreasing the fuel-air ratio increases the cycle efficiency. It must be remembered, however, that the mechanical efficiency of the engine decreases as the fuel-air ratio is decreased. Therefore, the overall efficiency of the engine should reach a maximum value for one particular excess air coefficient.

The curves in Figures 14 to 18 are reproduced in Figure 19, together with other test data obtained in the same series. The fuel-injection pump setting was the same for all the runs. As the time of injection was advanced the time lag of ignition decreased until

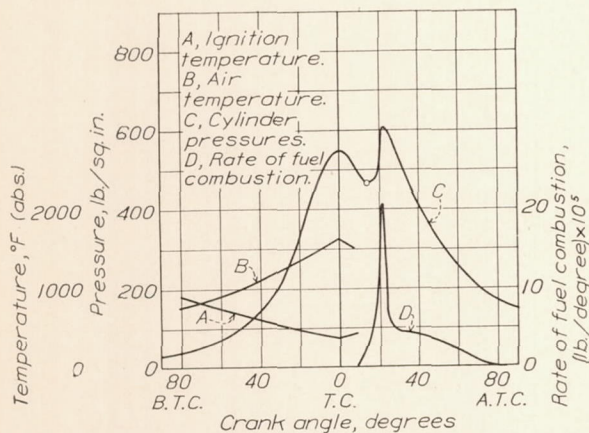


FIGURE 17.—Injection cut-off 14° A. T. C. Fuel-air ratio=0.0466 lb. fuel per lb. air. Supercharging pressure=8.75 in. Hg. i. m. e. p.=152 lb./sq. in. Cycle efficiency=42.5 per cent. Combustion efficiency=67 per cent. Thermal efficiency=28.4 per cent

finally a large portion of the fuel was burned while injection was taking place. This early burning resulted in a decrease in the rate of pressure rise. When all the fuel was injected before top center the time lag again increased and combustion was not started until all the fuel was in the combustion chamber. The rate of pressure rise again became excessive, with a resulting heavy knock. With combustion starting

close to or just after top center the engine showed little tendency to detonate. (Fig. 14.) However, with retarded injection, detonation (Fig. 16) was noticed. It can be concluded, therefore, from the test data and analysis that in a compression-ignition engine detonation can be eliminated by forcing com-

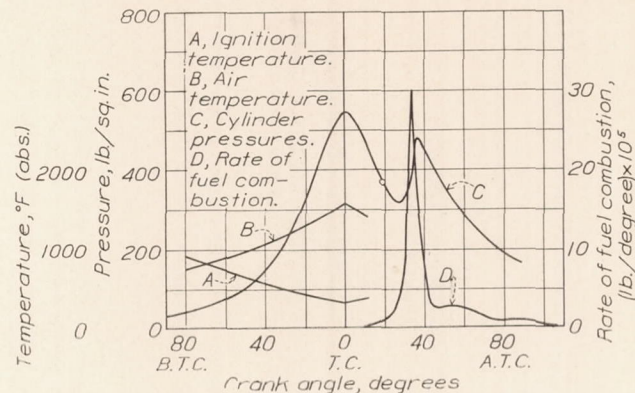


FIGURE 18.—Injection cut-off 19° A. T. C. Fuel-air ratio=0.0510 lb. fuel per lb. air. Supercharging pressure=8.75 in. Hg. i. m. e. p.=141 lb./sq. in. Cycle efficiency=36.1 per cent. Combustion efficiency=69.3 per cent. Thermal efficiency=25 per cent

bustion to start sufficiently early during the injection of the fuel to control the maximum rate of combustion.

Figure 20 shows a series of cards obtained at a supercharging pressure of 5 inches of mercury. The same tendency is noticed that was observed in Figures 13 and 19. Although the time lag was less than that obtained with no supercharging, it was greater than that obtained with 8.75 inches of mercury supercharging. In no case with the 5 inches of supercharging did combustion start early enough to be affected by the rate of injection.

Figure 21 shows the effect of the difference between the air temperature at A cut-off of injection and B start of combustion and the minimum autoignition temperature at the start of pressure rise on the time lag between cut-off and the start of pressure rise. A slight change in the temperature difference caused considerable change in the time lag. Of course, the true time lag is measured from the start of injection and not the end of injection as shown in the curve. The approximate time interval between the start of injection and the point of cut-off can be obtained from the rates-of-fuel-injection curves.

The effect of time lag between cut-off and the start of pressure rise on the combustion efficiency of the engine is shown in Figure 22. The results are in accordance with the dispersion of the sprays as indicated in Figure 7. It can be concluded that for a quiescent combustion chamber, as the time lag of ignition after the cut-off of the fuel spray is increased, the combustion efficiency and the tendency to detonate are increased. It must be remembered that the increase in combustion efficiency for these tests was more than balanced by the decrease in cycle efficiency, so that

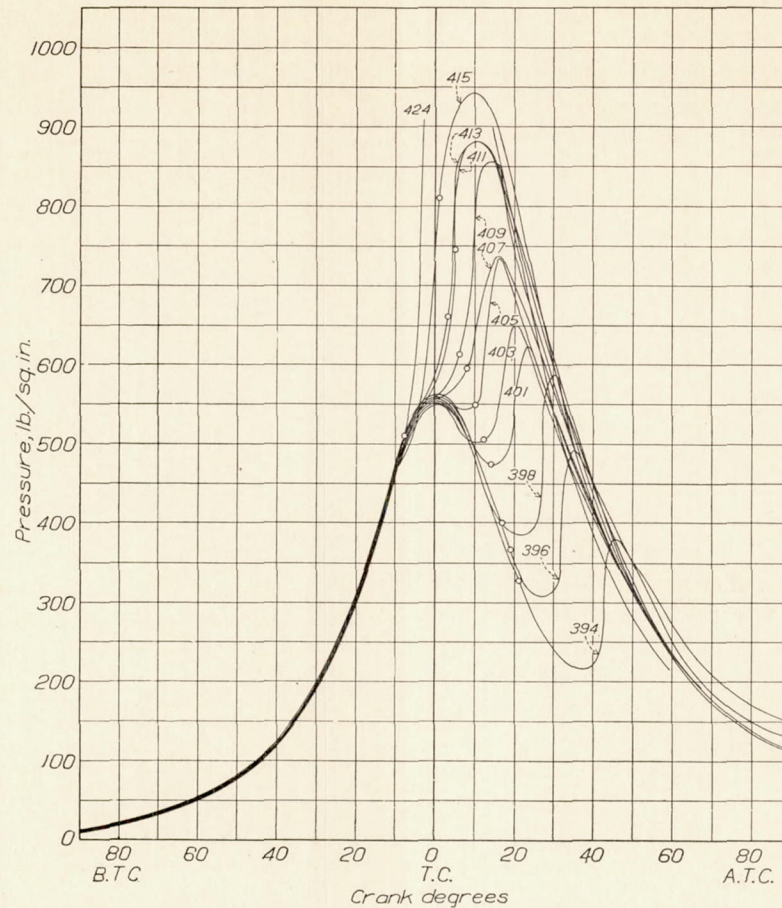


FIGURE 19.—Effect of injection advance angle on combustion. Supercharging pressure=8.75 in. Hg.

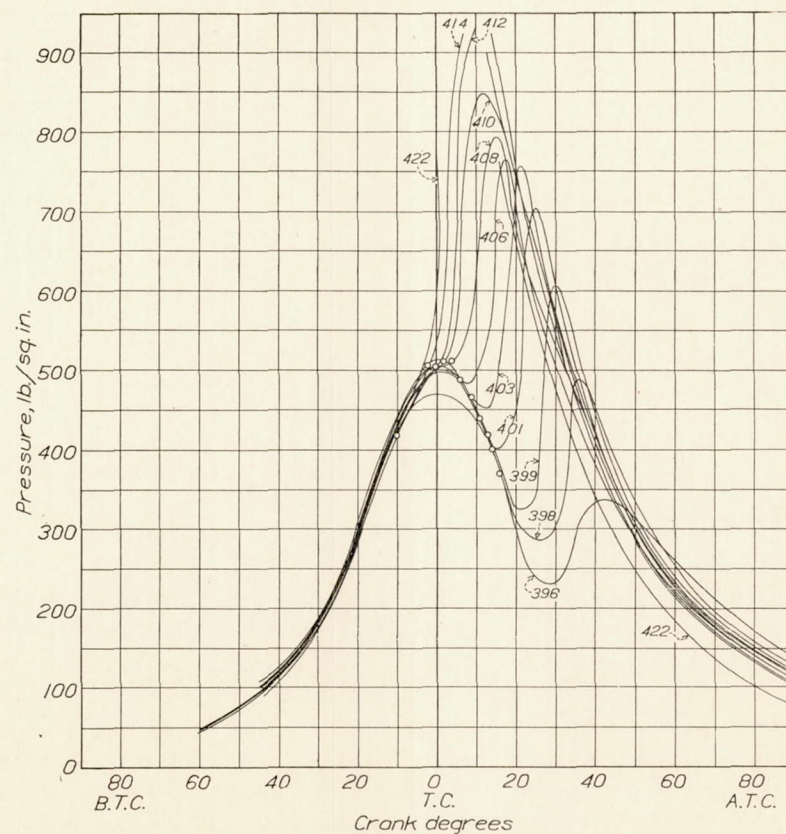


FIGURE 20.—Effect of injection advance angle on combustion. Supercharging pressure=5 in. Hg.

as the injection was retarded the thermal efficiency of the engine decreased.

Figure 23 shows the effect of the time lag between cut-off of the fuel spray and the start of pressure rise on the maximum rate of combustion. The curve shows the importance of forcing ignition to start during injection as a means of eliminating detonation. The high rates of combustion accompanied by high combustion efficiency for a large time lag are caused by the improved mixing of the fuel and air after injection has stopped. (Fig. 7.)

Effect of injection from double-stem injection valve.—The double-stem injection valve (reference 6) was designed to cause the injection of the fuel to take place at such a rate that the initial combustion

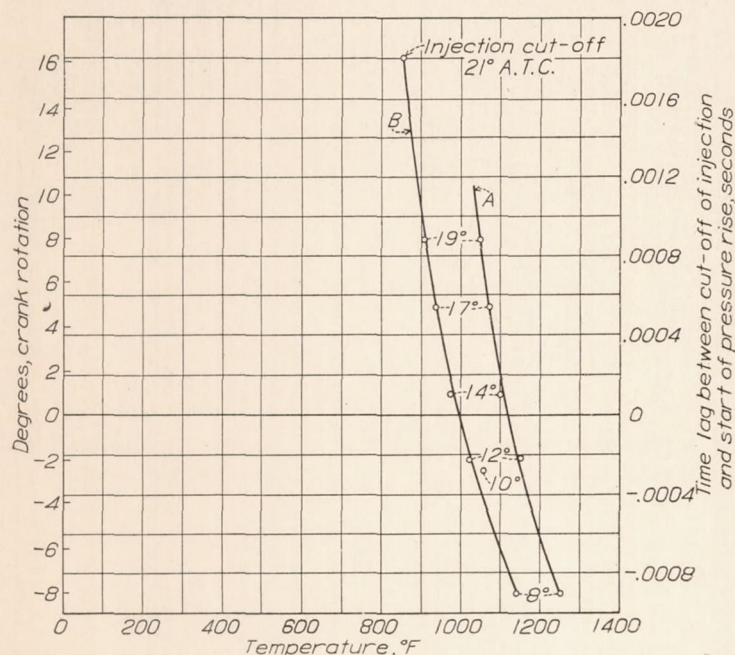


FIGURE 21.—Effect of difference between air temperature and minimum autoignition temperature at cut-off of injection and at start of combustion on time lag between injection cut-off and start of pressure rise. Supercharging pressure=8.75. in Hg. A=difference between air temperature and minimum autoignition temperature at start of combustion. B=difference between air temperature and minimum autoignition temperature at cut-off of injection.

would take place at top center at constant volume and the succeeding combustion take place at constant pressure. In this manner it was hoped to obtain a high cycle efficiency. The injection was started when the first stem was lifted and then proceeded from the orifices opened by this stem until the hydraulic pressure in the injection valve reached the pressure required to lift the second stem. At this point the fuel already injected was intended to burn at constant volume. The remainder of the fuel which was injected through all the orifices was intended to burn at constant pressure. A subsequent investigation (reference 25) showed that the contour of the cam of the fuel pump was not correct to give the desired rates of discharge, because the velocity of the portion of the cam designed for the initial injection was not sufficient to hold the primary stem from its seat. The indicator

cards obtained from the engine when this injection valve was used do, however, present interesting in-

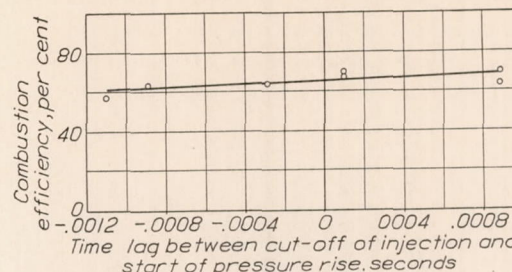


FIGURE 22.—Effect of time lag between cut-off of injection and start of pressure rise on combustion efficiency

formation which is of use in analyzing the combustion process. They are, therefore, presented, although the engine performance was not so good as that obtained with the single-stem injection valve.

Figures 24 and 25 show the effect of the injection from the double-stem injection valve on the combustion characteristics. In general, the rate of injection curves showed, first an increasing rate of injection, then a decreasing rate (at times reaching zero), followed by a curve of the same general shape as obtained with the single-stem valve. The results were caused either by a bouncing of the injection-valve stems or by the instantaneous pressures dropping rapidly after the start of injection because the rate of displacement at the injection pump was not sufficient to maintain the pressure on the injection valve stem required to hold the stem from the seat. Just how closely the results obtained with injection into the atmosphere approached the rates with injection into the engine can not be said. The indicator cards show that in every case the rates of combustion were influenced by a rate of injection of the same order as shown in the rate of injection curve. In no case did the maximum rate of combustion reach the values that were obtained with the single-stem valve. The exact cause of this is not known.

It is possible that the spray issuing into the com-

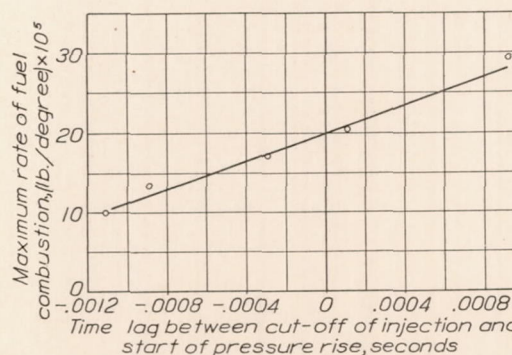


FIGURE 23.—Effect of time lag between cut-off of injection and start of pressure rise on maximum rate of fuel combustion

bustion chamber from the initial injection did not have sufficient power to penetrate far into the

combustion chamber. Consequently when this spray burned there was an area of hot gases through which the succeeding spray had to pass. Gelalles (reference 27) has shown that increasing the temperature of the air decreases the penetration of the fuel spray. In this case the succeeding fuel was unable to penetrate

CONCLUSIONS

The analysis of these indicator cards shows that the problem of obtaining efficient combustion without detonation in a high-speed compression-ignition engine suitable for aircraft service is one of controlling the mixture of the fuel and air and of controlling the start

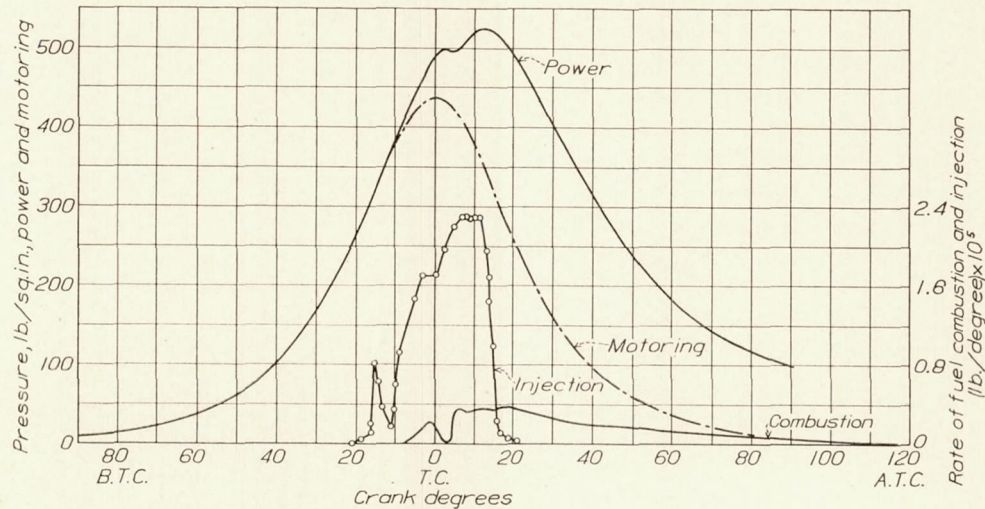


FIGURE 24.—Effect of double-stem injection valve on rate of fuel injection and on combustion. i. m. e. p.=118 lb./sq. in. Fuel injected=0.000430 lb. Fuel burned=0.000187 lb. Combustion efficiency=43.5 per cent. Cycle efficiency=50.5 per cent. Thermal efficiency=22 per cent

throughout the whole of the combustion chamber. The result was an overrich mixture close to the injection valve which retarded combustion until this mixture could diffuse with the remainder of the air. Therefore, there was a long period of after burning

of combustion. The results have shown that the rate of fuel injection does not in itself control the rate at which the fuel burns. The combustion can be caused to start sufficiently early in the cycle to obtain high cycle efficiencies without detonation by employing

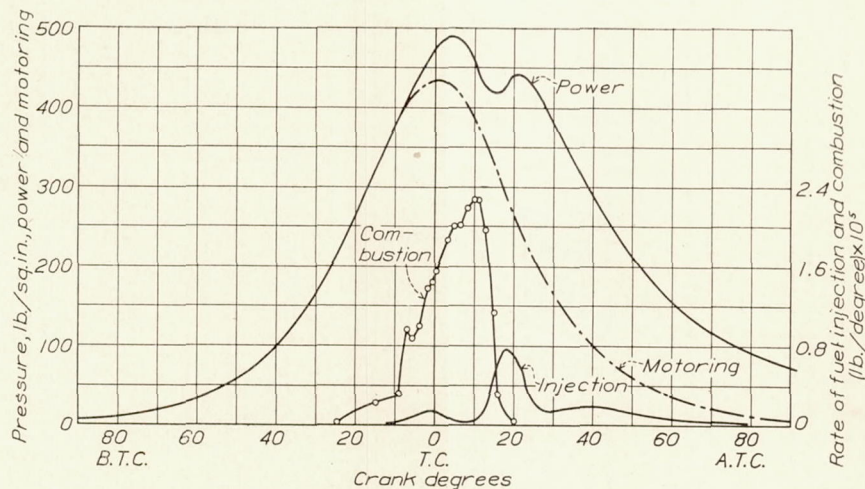


FIGURE 25.—Effect of double-stem injection valve on rate of fuel injection and combustion. i. m. e. p.=99 lb./sq. in. Fuel injected=0.000286 lb. Fuel burned=0.000143 lb. per cycle. Combustion efficiency=50 per cent. Cycle efficiency=55.5 per cent. Thermal efficiency=27.7 per cent

accompanied by a low cycle and combustion efficiency. The low cycle efficiency here refers to the cycle efficiency which would have been obtained (see fig. 14) had more of the fuel been burned at constant volume. The long period of after burning was further indicated by a smoky exhaust. (Reference 6.)

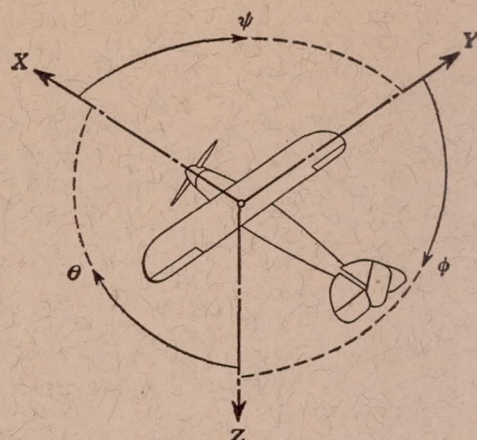
temperatures sufficiently higher than the minimum autoignition temperature of the fuel. By so doing the cycle efficiency of the engine can be raised to a value for which the power output of the engine will compare more favorably with the power output of present-day spark-ignition engines.

The problem of detonation in the compression-ignition engine is different from that in the spark-ignition engine in which all the fuel is injected before the spark takes place. In the conventional spark-ignition engine any change that increases the density and temperature in the combustion chamber increases the tendency for detonation to occur. Consequently, the compression ratio of the engine is limited by the properties of the fuel employed. On the other hand with the compression-ignition engine in which the fuel is injected during the end of the compression stroke and start of the expansion stroke, the tendency for the engine to knock is decreased with an increase in the inlet-air density (supercharging), with an increase in the compression ratio, or with an increase in the air temperature. It may be concluded that the development of the compression-ignition engine will be benefited by further investigations in the use of higher compression ratios, by supercharging, and by the use of heated air.

LANGLEY MEMORIAL AERONAUTICAL LABORATORY,
NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS,
LANGLEY FIELD, VA., May 21, 1931.

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Positive directions of axes and angles (forces and moments) are shown by arrows

Axis		Force (parallel to axis) symbol	Moment about axis			Angle		Velocities	
Designation	Sym- bol		Designation	Sym- bol	Positive direction	Designa- tion	Sym- bol	Linear (compo- nent along axis)	Angular
Longitudinal---	X	X	rolling-----	L	Y → Z	roll-----	φ	u	p
Lateral-----	Y	Y	pitching-----	M	Z → X	pitch-----	θ	v	q
Normal-----	Z	Z	yawing-----	N	X → Y	yaw-----	ψ	w	r

Absolute coefficients of moment

$$C_l = \frac{L}{qbS} \quad C_m = \frac{M}{qcS} \quad C_n = \frac{N}{qbS}$$

Angle of set of control surface (relative to neutral position), δ . (Indicate surface by proper subscript.)

4. PROPELLER SYMBOLS

D , Diameter.

p , Geometric pitch.

p/D , Pitch ratio.

V' , Inflow velocity.

V_s , Slipstream velocity.

T , Thrust, absolute coefficient $C_T = \frac{T}{\rho n^2 D^4}$

Q , Torque, absolute coefficient $C_Q = \frac{Q}{\rho n^2 D^5}$

P , Power, absolute coefficient $C_P = \frac{P}{\rho n^3 D^5}$

C_s , Speed power coefficient $= \sqrt[5]{\frac{\rho V'^5}{P n^2}}$

η , Efficiency.

n , Revolutions per second, r. p. s.

Φ , Effective helix angle $= \tan^{-1} \left(\frac{V}{2\pi r n} \right)$

5. NUMERICAL RELATIONS

1 hp = 76.04 kg/m/s = 550 lb./ft./sec.

1 kg/m/s = 0.01315 hp

1 mi./hr. = 0.44704 m/s

1 m/s = 2.23693 mi./hr.

1 lb. = 0.4535924277 kg.

1 kg = 2.2046224 lb.

1 mi. = 1609.35 m = 5280 ft.

1 m = 3.2808333 ft.